The spatial distribution of indigenous forest and its composition in the Wellington region, New Zealand, from ETM+ satellite imagery

John R. Dymond*, James D. Shepherd

Landcare Research, Private Bag 11052, Palmerston North, New Zealand

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Abstract

In order to improve biodiversity management in the Wellington region of New Zealand, it is necessary to make an inventory of the indigenous forest—where is it, and what type is it? The single greatest impediment to making a spatially (i.e., 1:50,000 scale) and thematically detailed inventory from satellite imagery has been the topography of the three mountainous ranges in the Wellington region. The effective irradiance of incoming light varies with slope orientation, as does the proportion of light that is reflected towards the satellite (the bidirectional reflectance). In this paper, we show how satellite imagery may be processed to standardised spectral reflectance, which is a property of the vegetation alone, independent of sun position, slope, and view direction. Because of this, the use of automatic methods to map vegetation and provide spatially and thematically detailed maps is greatly simplified. Using this method, we produce a land-cover map of the Wellington region, with eight classes, to a classification accuracy of approximately 95%. We also show how the proportions of conifer, broad-leaved, and beech trees may be determined for indigenous forest to provide a framework for forest-type inventory.

Keywords: Indigenous forest; Topographic correction; Bidirectional reflectance; Forest inventory; Standardised reflectance; Biodiversity

1. Introduction

The Wellington region, in the lower part of the North Island (Fig. 1), New Zealand, has 23% of its 813,000 ha covered in indigenous forest. In pre-Maori times, nearly all the Wellington region was covered by indigenous forest, but after the arrival of Maori (ca. 1000 A.D.), a significant proportion was burned for shifting agriculture, and after the arrival of Europeans (ca. 1840 A.D.) an even larger proportion was burned and cleared for pastoral agriculture. Most of the indigenous forest is now confined to the protected mountainous areas of the Tararua, Rimutaka, and Aorangi forest parks. There are also many small remnants of indigenous forest spread throughout the rest of the region, and there are large blocks of shrubland reverting to indigenous forest on the east coast. In response to the Convention on Biological Diversity, land managers in New Zealand are increasingly concerned with identifying and protecting indigenous habitats for biodiversity. An important part of a regional approach to biodiversity management is an inventory of the indigenous forest. We need to know where it is and what type it is.

The climate of the Wellington region is mild and wet: annual rainfall varies between 800 mm in the eastern Wairarapa and 7000 mm at the tops of the Tararua range (ca. 1500 m), and mean monthly temperatures at Wellington city range between 8 °C in July and 16 °C in January. The forests of the region are dominated by various mixtures of species from three groups: conifers, all from the Podocarpaceae family (Table 1); broad-leaved evergreen species from a wide range of families (Table 2 lists the more common broad-leaved species); and four species of Nothofagus, or southern beech (Table 3). Forests dominated by broad-leaved trees with scattered emergent conifers (conifer/broadleaf forest) occur on most lowland sites, although conifers have been selectively removed by logging over sometimes large areas to leave forests now dominated by broad-leaved species. Conifer/broadleaf forest is usually luxuriant with small trees, shrubs, and ferns forming understoreys, and mosses, lichens, lianes, and epiphytes are plentiful. There is a general shift to dominance by Nothofagus (beech forest) at higher elevations, or on sites with dry climates or infertile soils. Beech forest tends to be domi-
nated by just one or more of the southern-beech species and has a generally lower diversity of associated plant species.

The first indigenous forest map of New Zealand (which included the Wellington region) was compiled by the Forest Service in the 1950s (Nicholls, 1957). A 1:250,000 scale map of 19 forest classes was produced from a combination of field work and interpretation of stereo black-and-white aerial photographs. Although of sufficient thematic resolution, the spatial resolution is not sufficient for regional management where 1:50,000 scale mapping is required.

The Ministry of Works and Development produced a vegetation map of New Zealand at 1:250,000 scale (Newsome, 1987) primarily from black-and-white aerial photographs. Again, although having high thematic resolution with some 30 forest types mapped, the spatial resolution is not sufficient for regional management. Landcare Research mapped the vegetation of the Wellington region at 1:50,000 from aerial photographs (Page, 1995). Although mapping was carried out at 1:50,000, the polygon boundaries primarily reflected landform, and the gross proportions of 12 forest types were recorded for each polygon. The most recent vegetation map of the Wellington region is the 1:50,000 scale Land Cover Database (LCDB) of New Zealand mapped from SPOT satellite images by the national mapping agency Terralink (the nominal mapping date was 1996–1997). It has reasonable spatial resolution with a 1-ha minimum mapping unit, but there is only one indigenous forest class. What is needed is a 1:50,000 scale map of indigenous forest in the Wellington region with high spatial and thematic resolution.

To combine high spatial detail with large area coverage, it is necessary to use automatic processing of satellite imagery. However, in the hilly and mountainous terrains

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**Table 1**

Indigenous conifer trees found in permanent forest plots of the Wellington region

<table>
<thead>
<tr>
<th>Maori name</th>
<th>Scientific name</th>
<th>Common name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rimu</td>
<td><em>Dacrydium cupressinum</em></td>
<td>Red pine</td>
</tr>
<tr>
<td>Kahikatea</td>
<td><em>Dacrycarpus dacrydioides</em></td>
<td>White pine</td>
</tr>
<tr>
<td>Miro</td>
<td><em>Prumnopitys ferruginea</em></td>
<td>Brown pine</td>
</tr>
<tr>
<td>Matai</td>
<td><em>Prumnopitys taxifolia</em></td>
<td>Black pine</td>
</tr>
<tr>
<td>Totara</td>
<td><em>Podocarpus totara</em></td>
<td>Totara</td>
</tr>
<tr>
<td></td>
<td><em>Podocarpus hallii</em></td>
<td>Hall’s totara</td>
</tr>
<tr>
<td></td>
<td><em>Phyllocladus alpinus</em></td>
<td>Mountain toatoo</td>
</tr>
</tbody>
</table>

The Ministry of Works and Development produced a vegetation map of New Zealand at 1:250,000 scale (Newsome, 1987) primarily from black-and-white aerial photographs. Again, although having high thematic resolution with some 30 forest types mapped, the spatial resolution is not sufficient for regional management. Landcare Research mapped the vegetation of the Wellington region at 1:50,000 from aerial photographs (Page, 1995). Although mapping was carried out at 1:50,000, the polygon boundaries primarily reflected landform, and the gross proportions of 12 forest types were recorded for each polygon. The most recent vegetation map of the Wellington region is the 1:50,000 scale Land Cover Database (LCDB) of New Zealand mapped from SPOT satellite images by the national mapping agency Terralink (the nominal mapping date was 1996–1997). It has reasonable spatial resolution with a 1-ha minimum mapping unit, but there is only one indigenous forest class. What is needed is a 1:50,000 scale map of indigenous forest in the Wellington region with high spatial and thematic resolution.

To combine high spatial detail with large area coverage, it is necessary to use automatic processing of satellite imagery. However, in the hilly and mountainous terrains

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**Fig. 1. Location map of the Wellington region.**
extensive in New Zealand, the apparent radiance (i.e., brightness) of vegetation is a function not only of vegetation reflectance, but also of solar elevation, slope orientation, and satellite view direction (Hugi & Frei, 1983; Teillet, Guidon, & Goodenough, 1982). With varying slope orientation, the effective irradiance of incoming light varies from place to place, as does the proportion of irradiance reflected towards the satellite (i.e., bidirectional reflectance). These topographic effects have hampered the automated mapping of vegetation in New Zealand (Dymond, Page, & Brown, 1996) and in other mountainous parts of the world (Conese, Gilabert, Maselli, & Bottai, 1993) for some time and is the main reason why visual interpretation of satellite imagery is still being used (Blasco, Bellan, & Aizpuru, 1996; Driese, Reiners, Merrill, & Gerow, 1997).

In this paper, we describe a satellite-based method for mapping the indigenous forest in the Wellington region at high spatial and thematic resolution. We show how to remove the confusing effects of topography by processing the imagery to standardised spectral reflectance, that is, reflectance on a flat surface, viewed from zenith, with a standard solar elevation. From standardised spectral reflectance, it is possible to map indigenous forest in an automatic way at high spatial resolution (i.e., 15-m pixels). We show it is possible to use characteristic spectral reflectances of the three basic types of forest (i.e., beech, conifer/broadleaf, and broadleaf) to obtain a continuum of proportions of conifer, broad-leaved, and beech trees. This continuum forms a framework useful for the monitoring and management of biodiversity in indigenous forest (Meenken, 2002).

### 2. Methods

We obtained two Landsat ETM+ images of the Wellington region dated 29 September 1999 and 4 December 2000. The two images were approximately 95% cloud-free and together gave a 99.9% cloud-free coverage of the Wellington region. ETM+ imagery has six spectral bands with 30-m pixel resolution: blue (0.45–0.52 μm), green (0.52–0.60 μm), and red (0.63–0.69 μm) visible bands; near-infrared (0.76–0.90 μm); and two short-wave infrared bands (1.55–1.75 and 2.08–2.35 μm). There is also a thermal band (10.4–12.5 μm) with 60-m pixels, which was not used. As well, there is a panchromatic band (0.52–0.90 μm) with 15-m pixels, which we combined with the 30-m multispectral data to produce 15-m multispectral pixels—a process termed pan sharpening. This permitted us to map at a scale of 1:50,000, the scale generally required by regional councils in New Zealand.

#### 2.1. Pan sharpening of ETM+ imagery

If imagery is to be used for automated classification, then pan sharpening must retain the integrity of the original spectral signatures associated with vegetation types: the commonly used fusion approach (Carper, Lillesand, & Kiefer, 1990), where the panchromatic band is assigned to the intensity band before inversion back to blue, green, and red, does not retain spectral integrity as intensity and hues are sourced from different areas. To achieve better spectral integrity, we used a local correlation filter as follows. For each 30-m pixel in a multispectral band, a 3 × 3 pixel window, centred on the pixel, is considered. A regression is established between the nine pixels of the window and the average of the corresponding pixels in the panchromatic band (each 30-m multispectral pixel is associated with the average of four 15-m panchromatic pixels). This regression is then applied to each of the four 15-m panchromatic pixels to obtain predictions of multispectral pixels. The process is repeated for each pixel in a multispectral band to form the pan-sharpened image.
2.2. Ortho-rectification

The pan-sharpened imagery was ortho-rectified using Erdas Imagine software. A digital elevation model (DEM) generated to 15-m pixels from existing 20-m digital contours was used. Approximately 25 ground control pairs spread evenly throughout the imagery were used for rectification. We used pairs to help identify whether errors were due to mapping or pointing. They came from an independent regional coverage of black-and-white ortho-photographs with 2.5-m pixels. The resulting RMS mapping error of the ortho-rectified satellite imagery was 20 m.

2.3. Processing to standardised spectral reflectance

The radiance (i.e., apparent brightness) of vegetation as seen by a satellite is essentially the product of the irradiance (i.e., the amount of light falling on the vegetation) and the vegetation reflectance (i.e., the proportion of irradiance reflected), attenuated through the atmosphere. Both the irradiance and reflectance are influenced by the position of the sun relative to the slope normal of the vegetation surface. Reflectance is also influenced by the viewing direction of the satellite relative to the slope normal. Hence, in a satellite image of hilly or mountainous terrain, the apparent radiance of vegetation is strongly influenced by topography. It is desirable for a satellite image to represent only the properties of the vegetation, or other reflecting surfaces. To achieve this, it is necessary to process the satellite image to standardised spectral reflectance, which is the spectral reflectance of the vegetation assuming flat terrain with the sun and satellite in standard positions (we usually assume a nadir view for the satellite, and a solar elevation of 50°—this elevation is regularly achievable in summer and desirable for maximising the information content of vegetation). Processing of satellite imagery to standardised reflectance involves physical modelling of radiation: from the sun and sky through the atmosphere; reflection of the light from the vegetation canopy; and the transmission of the reflected light through the atmosphere to the satellite sensor. We used the 6S code (Tanre et al., 1990) to model irradiance and transmission of light through the atmosphere, and WAKII (Dymond, Shepherd, & Qi, 2001) to model bidirectional reflectance of vegetation.

The 6S code predicts the direct and diffuse irradiance from a cloudless sky onto a horizontal surface at a given altitude. It requires aerosol, water vapour, and ozone concentrations, which we obtained from monthly climatological mean profiles acquired by ozonesonde. To generalise the horizontal surface predictions of 6S to a sloping surface, we simplified the formulation of Sandmeier and Itten (1997) to give the total solar irradiance $E(b,z)$ on a sloping surface as

$$E(b,z) = \theta E_{h}^{dir}(b,z) \frac{\cos i}{\cos h} + E_{h}^{diff}(b,z)V_d + E_{h}(b,z)V_i \rho_{adj}(b)$$

where $b$ is spectral band; $z$ is altitude; $E$ is total irradiance on a sloping surface; $E_{h}$ is total irradiance on a horizontal surface; $E_{h}^{dir}$ is the direct component of irradiance on a horizontal surface; $E_{h}^{diff}$ is the diffuse component of irradiance on a horizontal surface; $\theta$ is a binary coefficient, set to zero in cast shadow; $i$ is the angle of incidence between the surface normal and the sun; $h$ is the angle of incidence for a horizontal surface; $V_d$ is the sky-view factor; $V_i$ is the terrain-view factor; $\rho_{adj}$ is the average reflectance of adjacent vegetation.

The first term in Eq. (1) represents direct irradiance from the sun, which is set to zero in cast shadows. The second term represents diffuse irradiance and is a product of the diffuse component of irradiance on a horizontal surface with the fraction of sky seen, $V_d$, which is approximated by a trigonometric function (Kondratyev, 1969)

$$V_d = \frac{1 + \cos s}{2}$$

where $s$ is the slope angle. The third term in Eq. (1) represents terrain irradiance reflected from neighbouring slopes with an average Lambertian reflectance of $\rho_{adj}$. The terrain irradiance is weighted by the fraction of terrain seen, $V_t$, where

$$V_t = \frac{1 - \cos s}{2}$$

A high-resolution DEM (15-m pixels) enables Eq. (1) to calculate the total irradiance on any slope from the horizontal surface values obtained from 6S. The only remaining term is $\rho_{adj}$, which is estimated from the mean atmosphere-corrected reflectance of the satellite image.

The radiance of vegetation on a sloping surface at the bottom of atmosphere, $L$, is related to the irradiance as follows:

$$L = \frac{\rho^{dir}E^{dir} + \rho^{diff}E^{diff}}{\pi}$$

where $\rho^{dir}$ is the vegetation reflectance for direct light, $E^{dir}$ is the direct irradiance, $\rho^{diff}$ is the vegetation reflectance for diffuse light, and $E^{diff}$ is the diffuse irradiance (reflectances are assumed to be in the direction of the observer). $L$ at the bottom of atmosphere may be determined by applying the 6S code to $L$ observed at the top of atmosphere (i.e., the original satellite image after calibrating to radiance). The task then is to calculate $\rho^{dir}$ from $L$ at the bottom of atmosphere, given that we have now modelled $E^{dir}$ and $E^{diff}$, and then to transform to the equivalent reflectance on a horizontal surface, that is, $\rho^{dir}$.

Assuming that $\rho^{diff}$ is some multiple, $\beta$, of the direct reflectance, which may be calculated on a case-by-case basis using the WAKII model, and following the method of Dymond and Shepherd (1999), which relates horizontal reflectance to sloping reflectance as

$$\rho^{dir} = \frac{\cos i + \cos h}{\cos i + \cos h} \rho^{dir}_{h} = \gamma \rho^{dir}_{h}$$

where $\gamma$ is a constant.
where $i$ and $e$ are the angles of incidence and reflectance on the slope, and $i_h$ and $e_h$ are the standardised angles of incidence and reflectance on a horizontal surface, then Eq. (4) may be rewritten as

$$\rho_{\text{dir}} = \frac{\pi L}{E_{\text{dir}}/\gamma + \beta E_{\text{dir}}}$$

Eq. (6) now gives the direct reflectance of vegetation on a horizontal surface and is a vegetation attribute independent of sun-surface-satellite geometry that we term standardised reflectance. It is applicable whenever the WAKII model is applicable, which is when land is covered primarily in vegetation (Dymond et al., 2001). When reflectances are calculated for each spectral band, we term this standardised spectral reflectance and denote it by $\rho_n$, where $n$ refers to the particular ETM+ spectral band. Fig. 2 shows a portion of an ETM+ satellite processed to standardised spectral reflectance. A more detailed description for standardising spectral reflectance is given by Shepherd and Dymond (2003).

2.4. Mapping indigenous forest extent

The spatial extent of indigenous forest was mapped along with other basic land covers using a hierarchical set of binary split rules, as shown in Fig. 3. There were several reasons why a hierarchy of rules was chosen: the land covers naturally organise themselves into a hierarchy; different discrimination functions at each decision node could be used (Jia & Richards, 1998); and also because binary discriminant functions (i.e., the rules) can be expressed very simply, which is an advantage when repeat mapping, for environmental monitoring, requires execution of the same rules. The rules were developed by visual examination of typical spectral signatures at each node to produce several trial rules. The final rule at a node was chosen by an iterative process of trial and error to minimise the number of incorrectly mapped pixels from a selection of ground data sites. The rules enable objective definition for each land cover as shown by Table 4.

As the rules are defined using standardised spectral reflectance, they should be reasonably stable in time and able to be used repeatedly with little modification. Some of the binary splits are not perfect and required some manual editing to tidy up some obvious errors, such as vegetation spots in the ocean and lakes, water spots in urban bare ground, and woody vegetation where there should have been field crops. Due to a great range of spectral signatures for planted conifer forest, the final split into indigenous forest and planted conifer forest was created by imposing a planted conifer layer on the forest class. The planted conifer layer was created semiautomatically by manually seeding each forest lot, on a 4-5-3 band RGB band combination, and automatically growing regions to the forest lot edge. A final cleanup of small patches mapped as indigenous forest, but which were actually other uncom-
common vegetation types, to unspecified woody vegetation was also required. This was done by visually checking against the standardised imagery indigenous forest patches in landscapes containing unusual vegetation patterns. Patches requiring cleanup involved less than 1% of the study area.

2.5. Determining composition of indigenous forest

The standardised spectral reflectance of indigenous forest is controlled by the proportions of beech, broadleaf, and conifer/broadleaf forest types, as each type has its own characteristic spectral reflectance. These characteristic spectral reflectances were reasonably consistent throughout the Wellington region in the September ETM+ image. Given this spatial consistency, it is possible to determine the proportions of beech, conifer, and broadleaf trees. We used a procedure based on angles between spectral reflectance and characteristic spectral reflectances. This essentially looks at the differences in hue between the spectral reflectance and the characteristic spectral reflectances. These 20-m plots are spread throughout the Tararua, and the adjustment was verified with data from 277 historical forest plots. This method was more successful than standard linear unmixing methods (Adams et al., 1995) which failed to produce the general regional pattern of forest composition as mapped by Newsome (1987) and Page (1995). It appears as though hues, which represent the direction of spectral reflectance vectors, characterise indigenous forest types more reliably than spectral reflectances. The adopted procedure is described below.

The characteristic spectral reflectance of mature beech, broadleaf, and conifer/broadleaf forest stands was determined by inspection of the standardised spectral reflectance image at known pure stands. We denoted these three characteristic spectral reflectances by \( p_b \), \( p_{bl} \), and \( p_{cb} \), where the underscore refers to the five-dimensional vector of standardised spectral reflectance from bands 2–6 (the blue band was excluded because of its relatively low signal-to-noise ratio). The proportional contribution of beech, conifer, and broad-leaved trees at any pixel of indigenous forest, denoted by \( \rho \), is calculated using a distance metric in spectral reflectance space based on the angles between the characteristic spectral reflectances and \( \bar{\rho} \).

\[
\cos \theta_b = \frac{\rho_b \cdot \bar{\rho}}{|\rho_b| \cdot |\bar{\rho}|},
\]

\[
\cos \theta_{bl} = \frac{\rho_{bl} \cdot \bar{\rho}}{|\rho_{bl}| \cdot |\bar{\rho}|},
\]

\[
\cos \theta_{cb} = \frac{\rho_{cb} \cdot \bar{\rho}}{|\rho_{cb}| \cdot |\bar{\rho}|}
\]

Weights are assigned to each forest type, as follows

\[
w_b = 1/\theta_b^2,
\]

\[
w_{bl} = 1/\theta_{bl}^2,
\]

\[
w_{cb} = 1/\theta_{cb}^2
\]

The proportions of beech, conifer, and broad-leaved trees (\( p_b, p_{bl}, p_{cb} \)) may then be calculated by weighting the distances, and adjusting for the average proportion of broad-leaved trees in conifer/broadleaf forest, which is approximately 70% (Adams et al., 1995, performed a similar adjustment by redefining image end-members as mixtures of reference end-members). The rationale behind the adjustment is that the procedure estimates the proportion of forest types, two of which contain broad-leaved trees, and to move to an estimate of proportions of tree types, it is necessary to know the average proportion of broad-leaved trees in conifer/broadleaf forest.

\[
p_b = \frac{w_b}{w_b + w_{bl} + w_{cb}}.
\]

\[
p_{bl} = \frac{w_{bl}}{w_b + w_{bl} + w_{cb}} + 0.7w_{cb}
\]

\[
p_c = \frac{0.3w_{cb}}{w_b + w_{bl} + w_{cb}}
\]

3. Results

The procedure for mapping indigenous forest composition was verified with data from 277 historical forest plots. These 20 × 20-m plots are spread throughout the Tararua,
Rimutaka, and Aorangi ranges and were last measured primarily in 1985 (Bellingham, Stewart & Allen, 1999 described the procedure for measuring the permanent plots). The sampling scheme is essentially cluster sampling of 70 random locations from approximately two-thirds of the total indigenous forest in the region. We assumed that the proportions of forest types have not changed substantially since that time. The species and trunk diameter of each tree in the plot was recorded. The map location of each plot was recorded to an accuracy of only $\pm 250$ m (Peter Bellingham, personal communication), and thus, it was not possible to position forest plots on their corresponding image pixels. Instead, we lumped the plots into groups of similar predicted proportions and plotted the predicted means versus the measured means of the groups. Figs. 4, 5, and 6 show the results.

A land-cover map of the Wellington region was produced at 1:50,000 scale. This required 10 map sheets with extents of $40 \times 30$ km (not reproduced in this article). Table 5 gives the area of each land cover in the Wellington region. Herbaceous vegetation is the largest cover class because pastoral agriculture is the dominant land use. Indigenous forest is the second largest cover due to the existence of the large Tararua, Rimutaka, and Aorangi forest parks. Planted conifer forest is the third largest cover class, with large forests in the coastal hill country of the Wairarapa. Narrow-leaved scrub, dominated by manuka ($\textit{Leptospermum scoparium}$) and kanuka ($\textit{Kunzea ericoides}$), is the fourth largest cover class, with large blocks on the Wairarapa coastal hill country where formerly pastoral land is reverting back to indigenous forest.

<table>
<thead>
<tr>
<th>Land cover</th>
<th>Area in hectares ($\pm$ 1000)</th>
<th>Percentage of region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>9700 ($\pm 1000$)</td>
<td>1.2</td>
</tr>
<tr>
<td>Bare ground</td>
<td>35,000 ($\pm 2000$)</td>
<td>4.3</td>
</tr>
<tr>
<td>Herbaceous vegetation</td>
<td>388,000 ($\pm 5000$)</td>
<td>47.9</td>
</tr>
<tr>
<td>Narrow-leaved scrub</td>
<td>79,000 ($\pm 4000$)</td>
<td>9.7</td>
</tr>
<tr>
<td>Broad-leaved scrub</td>
<td>31,000 ($\pm 2000$)</td>
<td>3.8</td>
</tr>
<tr>
<td>Indigenous forest</td>
<td>184,000 ($\pm 5000$)</td>
<td>22.7</td>
</tr>
<tr>
<td>Planted forest</td>
<td>49,000 ($\pm 2000$)</td>
<td>6.0</td>
</tr>
<tr>
<td>Unspecified woody</td>
<td>35,600 ($\pm 2000$)</td>
<td>4.4</td>
</tr>
<tr>
<td>vegetation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Undefined</td>
<td>1000</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total area</strong></td>
<td><strong>813,000</strong></td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>

Error limits give approximately 95% confidence limits as derived from the method of Dymond (1992).
To assess the classification accuracy of land cover, we generated a random selection of 100 points for each mapped land cover and noted the actual land cover as observed in digital ortho-photographs over the same 15 m area. Misregistration of up to 15 m between the land-cover map and the ortho-photographs was permitted. Table 6 presents the mapping accuracy of each class. The accuracies are all in the high nineties, with an average mapping accuracy of 95%. The high accuracy, which we believe to be primarily due to mapping from standardised spectral reflectance, gives confidence of good correspondence between mapped and actual land cover.

The pattern of narrow-leaved scrub and broad-leaved scrub intermingled with indigenous forest gives an insight into the status of indigenous forest and the succession back to indigenous forest. For example, on the western edge of the Tararua forest park, there is much broadleaf scrub resulting from historic milling of mature conifer trees. In

<table>
<thead>
<tr>
<th>Class data</th>
<th>Orthophoto data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water</td>
</tr>
<tr>
<td>Water</td>
<td>97</td>
</tr>
<tr>
<td>Bare ground</td>
<td>94</td>
</tr>
<tr>
<td>Broad-leaved scrub</td>
<td>1</td>
</tr>
<tr>
<td>Herbaceous vegetation</td>
<td>2</td>
</tr>
<tr>
<td>Indigenous forest</td>
<td>2</td>
</tr>
<tr>
<td>Narrow-leaved scrub</td>
<td>2</td>
</tr>
<tr>
<td>Planted conifer forest</td>
<td>2</td>
</tr>
<tr>
<td>Unspecified woody vegetation</td>
<td>6</td>
</tr>
</tbody>
</table>

For each class in the land-cover map, 100 random points were generated, and the actual land cover, as observed on orthophotos, was observed.

Fig. 7. Map of the indigenous forest composition of the Wellington region at an approximate scale of 1:1,000,000. The original data are sufficiently detailed to be plotted at 1:50,000 scale. The map shows a continuum of the proportion of beech (red), broadleaf (green), and conifer trees (blue).
contrast, on the eastern edge of the park, narrow-leaved scrub is mixed with broad-leaved scrub, indicating greater disturbance in the past, possibly full clearance or greater vulnerability to fire or landsliding. The broadleaf areas (31,000 ha) indicate a more rapid succession to indigenous forest, as narrow-leaved scrub (79,000 ha) is usually manuka or kanuka which can take over 100 years before species typical of mature forest begin to dominate. This spatial pattern of forest succession is helpful in identifying indigenous forest remnants for conservation. If all the broad-leaved and narrow-leaved scrub was left to revert, then over 110,000 ha could be added to the indigenous forest estate.

For the indigenous forest areas, the proportions of beech, broad-leaved, and conifer trees were calculated and mapped at 1:50,000 scale. Fig. 7 shows the map at an approximate scale of 1:1,000,000. Beech forest is dominant in the eastern half of the Tararua forest park, along the eastern edge of the Rimutaka forest park and in Aorangi forest park. Broad-leaved forest is dominant on the western side of the Tararua forest park. Generally speaking, everywhere else is a mixture of conifer and broad-leaved trees, signifying conifer/broadleaf forest. The accuracy of the indigenous forest composition map was checked against the New Zealand Land Resource Inventory (NZLRI), which mapped the proportions of forest types within landform polygons (Page, 1995). The proportion of polygons within which there was inconsistency between the NZLRI and the indigenous forest composition map was only 10%.

4. Discussion

The processing to standardised spectral reflectance removed the effects of topography, both the illumination and the bidirectional reflectance effects. It was this processing that permitted automated mapping using the land-cover rules and the mapping of indigenous forest composition. The high average mapping accuracy of 95% gives reasonable confidence of correspondence of mapped land cover with actual land cover. In a mountainous and hilly country like New Zealand, processing satellite imagery to standardised spectral reflectance should be routinely used before interpretation of imagery. Not only will it be useful for processing single images, but also for processing a temporal sequence of images in environmental monitoring: since standardised spectral reflectance is a property of the vegetation alone, without the influence of sun position, atmosphere, or satellite view direction. With a temporal sequence of standardised spectral reflectance, it might be possible to monitor the grazing effects of goats, deer, and possums on indigenous forest.

The mapping of indigenous forest at 1:50,000 scale proved successful, with the 15-m pixels enabling 1:50,000 maps to be printed with clarity. Not only was there high spatial detail, but the forest composition was mapped as a continuum of proportions of beech, broad-leaved, and conifer trees. From the continuum, it is a simple matter to generate forest functional groups using rules of proportions. The overall spatial pattern of forest composition agreed well with the NZLRI polygons, which were derived by traditional photo-interpretation and field survey. Unfortunately, it was not possible to check the predictions of individual pixels, as the forest plots had a locational uncertainty of up to 250 m. However, another national survey of forest plots is presently underway, and this survey is locating plots accurately with GPS units. We will then be able to test the predictions of individual pixels, and the large time lag between 1985 and 1999 will also be nullified with the new data. The mapping of indigenous forest composition relied on the regional consistency of characteristic spectral reflectances. There was consistency in the September ETM+ image, but not the December image. As understanding of seasonal changes in forest canopy colour and texture is still limited, care will be necessary to ensure regional consistency of characteristic spectral reflectances when applying this methodology to other regions.

Driese et al. (1997) pointed out that a digital map is a tool for vegetation analysis. We have combined the basic land-cover map with digital maps of rivers and streams to produce a map of riparian trees and shrubs. Intersection with catchment boundaries can produce statistics on the proportion of riparian zones with protective vegetation. Digital land-cover maps can also be combined with climate and soil information to improve the accuracy of spatial modelling of vegetation attributes (e.g., carbon density, canopy height), such as the GLM (generalised linear modelling) analysis by Leathwick and Mitchell (1992) and the GAM (generalised additive modelling) analyses by Leathwick (1995, 1998) and Frescino, Edwards, and Moisen (2001). We intend to investigate a variety of methods of combining satellite derived information with climate and soil data, including GAM modelling of the climate and land cover; stratification first with the land cover and then GAM modelling with the climate data; Bayesian updating of the land cover with the climate; and k nearest-neighbour regression on standardised spectral reflectance and Bayesian combination with climate data.

The 1:50,000 scale is sufficiently spatially detailed to aid regional management of biodiversity. The Wellington regional council is already using the forest composition map, in combination with the Land Environments data set (Leathwick et al., 2003), to prioritise indigenous forest remnants for conservation. Although the methodology is designed for the regional scale, it is able to be applied over the whole country. Landsat ETM+ images have areal extents of 180 × 180 km and currently cost NZ $1,500. Approximately 35 ETM+ images would be required to cover New Zealand at a cost of around NZ $50,000. Hence, application of the methodology over all New Zealand at a scale of 1:50,000 would be cost-effective compared with previous national mapping exercises.
5. Conclusions

Our results demonstrate the feasibility of processing satellite imagery to standardised spectral reflectance, which is reflectance of a flat surface, viewed from above, and with the sun at a standard position. Standardised spectral reflectance is a property of the vegetation alone and is independent of topography. This permits the use of automated computer classification to produce spatially detailed (i.e., 1:50,000 scale) land-cover maps. A land-cover map of the Wellington region (813,000 ha), New Zealand, was produced from standardised spectral reflectance to an average classification accuracy of 95%. The area of indigenous forest is 184,000 (+ 5000) ha, and the area of scrub reverting back to indigenous forest is 110,000 (+ 5000) ha. Standardised spectral reflectance also permits the production of maps of indigenous forest composition, that is, the proportion of beech, conifer, and broad-leaved trees. Indigenous forest composition and the spatially detailed land-cover maps form a framework useful for the regional management of biodiversity.

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